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COST-EFFECTIVENESS OF AFLATOXIN CONTROL METHODS: ECONOMIC INCENTIVES

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Multiple sectors within U.S. crop industries—growers, elevators, handlers/shellers, processors, distributors, and consumers—are affected by aflatoxin contamination of commodities, and have the potential to control it using methods developed at both the pre- and postharvest levels. While methods exist, adoption is low; thus, we seek to investigate ways to increase adoption. We believe there are at least three ways to improve adoption of existing aflatoxin control techniques: (1) providing economic incentives; (2) proving and or improving cost-effectiveness of the control methods; and (3) education/outreach across all the relevant industry sectors. Frequently within a commodity there is a mismatch in economic incentives, such that different sectors bear the brunt of aflatoxin costs at disproportionate rates. For example, corn and cottonseed growers bear most of the cost for aflatoxin control, whereas in peanuts and tree nuts, shellers and handlers incur the costs of aflatoxin control. Thus, peanut and tree nut growers may have no economic incentive to apply preharvest aflatoxin control. Postharvest control options are limited and in many cases are not yet approved by the EPA or FDA. The Kaldor-Hicks efficiency criterion may help to resolve this economic dilemma. If this criterion was to be applied to aflatoxin control in peanut and tree nuts, growers could be compensated by shellers/handlers to adopt preharvest aflatoxin control methods. However, the control methods must be cost-effective for this compensatory arrangement to work. We present three case studies of cost-effectiveness to reduce aflatoxin contamination in different crops: AF36 in cottonseed, Bt in corn, and Afla-Guard in peanuts.

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Introduction

Aflatoxin, perhaps the most well-known mycotoxin, is mainly produced in field crops by the fungi *Aspergillus flavus* and *A. parasiticus* (Council for Agricultural Science and Technology [CAST], 2003). Fungal contamination and subsequent production of aflatoxin can occur in crops while growing in the field, at harvest, during postharvest operations, and in storage. Aflatoxin B_1 is one of the most potent human chemical liver carcinogens known, and can cause stunting in children and immune system disorders (Turner et al., 2003). It also causes numerous adverse effects in different animal species. In poultry, these include liver damage, reduced productivity, and increased disease susceptibility (Wyatt, 1991). Aflatoxin causes liver damage in swine; in cattle, milk production is reduced (Keyl, 1978) and aflatoxin M_1 is excreted in the milk.

The presence of aflatoxin in foods is restricted in the United States to the minimum levels attainable by modern processing techniques. The U.S. Food and Drug Administration's (FDA) action level for total aflatoxins in human food is 20 ng/g. However, a California Federal Marketing Order has established a stricter aflatoxin standard in pistachios of 15 ng/g. Action levels are also set for various categories of animal feed. Many other nations have established aflatoxin standards in food and feed (Food and Agriculture Organization [FAO], 2004).

Several economic studies have estimated costs associated with aflatoxin contamination in food and feed crops. In the United States, most of the costs associated with aflatoxin contamination are economic and not health-related because of effective food and feed screening methods. Vardon and colleagues (2003) estimated the annual cost associated with aflatoxin contamination in the United States at about $500 million through two categories of loss: market rejection and animal health impacts. Robens and Cardwell (2003) calculated the additional annual costs of aflatoxin management in the United States at $20–$50 million. Globally, the costs associated with human and animal health effects of aflatoxin consumption are much larger. Lubulwa and Davis (1994) calculated aflatoxin's "social" costs—human liver cancer, animal diseases, and market rejection—in three Asian nations to be $1 billion annually. Otsuki and colleagues (2001) estimated that compliance with the European Union (EU) aflatoxin standard of 4 ng/g in food costs African exporters $670 million U.S. dollars annually; however, their model did not account for actual trade volumes nor actual aflatoxin concentrations in the African crops. Wu (2004) went a step further and examined the actual trade volumes of peanuts and aflatoxin concentrations in Africa as well as the United States, China, and Argentina, which are the three largest peanut exporters in the world. She found that if the U.S. standard of 20 ng/g aflatoxin were adopted globally, annual losses through market rejection to these peanut exporters would be about $92 million; whereas if the EU standard of 4 ng/g were adopted globally, annual losses would skyrocket to $450 million. There is unlikely to be any human health benefit if the 4 ng/g versus the 20 ng/g standard were adopted.

Economic Incentives to Control Aflatoxin

The economic impacts of aflatoxin contamination can vary greatly among affected food/feed commodities. These differences include the severity of the contamination problem, the geographic range of aflatoxin problems, the types of aflatoxin control methods available, and which sectors bear the burden of the cost of aflatoxin contamination. All of these factors affect whether aflatoxin control methods are adopted.

Corn

Aflatoxin levels in U.S. corn and the economic impacts of aflatoxin control and contamination can vary substantially by geographic region. In the south, it is a perennial problem for dryland growers, whereas in the Midwest, severe aflatoxin levels occur less frequently, correlated with weather conditions (Stubblefield et al., 1991).

Corn growers experience the bulk of the economic loss of aflatoxin-related problems. Most corn with high aflatoxin levels is discarded before it enters the marketplace. The amount that growers must pay for testing varies year by year, depending on whether climatic conditions favor aflatoxin accumulation. In a "good" season (in which low levels of aflatoxin are expected), fewer loads are tested; but in a "problem" year, every load may be tested, at a cost of $10 to $20 per load (David Gibson, Texas Corn Producers Board, personal communication). This is a significant up-front cost to growers at harvest. Grain elevator operators incur aflatoxin-related costs as well. They must segregate corn with <20 ng/g aflatoxin for food, dairy, and young poultry markets, and corn with <300 ng/g aflatoxin for other feed; this increases labor and overhead costs. Once the corn is purchased, processors often retest it, adding to the total costs incurred with respect to aflatoxin. If corn is downgraded from food grade to feed grade, growers lose approximately $1 per bushel; if it is unacceptable even for feed grade, growers lose about $3 per bushel (Vardon et al., 2003).

In addition to the aforementioned aflatoxin-related costs, more money is spent to dispose of contaminated corn before it goes to market. In 2005–2006, southern corn growers experienced particularly high aflatoxin levels over a large portion of their acreage, necessitating some to discard over 50% of their crop. In 2006, 24 of 227 corn samples collected throughout Missouri had aflatoxin levels ranging from 10–89 ng/g (Missouri Department of Agriculture [MDA], 2006). Out of 62 corn samples in the Texas Panhandle and eastern Texas, 16 had aflatoxin levels between 20 and 300 ng/g and 15 had aflatoxin levels exceeding 300 ng/g (Texas A&M University [TAMU], 2006). A combination of a long drought season, overplanting following early rains, and an unusually hot early season led to plants that were overly stressed and more susceptible to *A. flavus* colonization and aflatoxin production. It is insufficient to simply calculate economic impact as the value of the disposed crop; such damage frequently puts growers out of business.

Corn-based ethanol production can also be affected by aflatoxin-contaminated corn, making it potentially cost-ineffective to produce. After ethanol production, the co-products can be used for animal feed, largely in the form of distillers' dried grains plus solubles (DDGS). However, the distillation process can concentrate the aflatoxin in the original grain up to three times in the DDGS (Murthy et al., 2005; Wu and Munkvold 2008).

Because 90% of DDGS produced in the United States enters the livestock and poultry feed chain, animal health effects due to higher aflatoxin levels in feed could pose an economic problem (Wu and Munkvold, 2008). Currently, there are few if any public surveillance programs in place for mycotoxins in DDGS, and there are not yet any published studies documenting an obvious decline in animal health from mycotoxins in DDGS. However, this use of corn further highlights the importance of aflatoxin control.

Cottonseed

Cottonseed makes up between 15% and 20% of cotton farmers' profit (Jaime-Garcia and Cotty, 2006); thus, aflatoxin contamination in cottonseed is an important economic concern. However, aflatoxin concentrations in cottonseed vary significantly by geographic region within the United States. While southeastern cotton growers do not often have problems with meeting aflatoxin standards for various cottonseed uses, growers in Texas, Arizona, and California have more severe contamination problems. Thus, as with corn, aflatoxin-related costs for cottonseed growers should be calculated by region to better represent the scope of the problem.

The dairy industry provides the largest market for cottonseed, because it can offer price premiums ranging from $30 to $80 per ton. The challenge to cottonseed producers is to provide cottonseed with aflatoxin levels below 20 ng/g, so that cows' milk will have aflatoxin M_1 levels below 0.5 ng/g. Milk containing aflatoxin concentrations above this limit can result in significant economic losses: milk must be discarded, cows must be quarantined, and lawsuits may ensue, potentially jeopardizing growers' and ginners' businesses. Another large market for cottonseed is oil; aflatoxin levels are less strict for this market because aflatoxin is presumed not to be present in significant quantities in oil. Because only about a dozen mills exist now in the United States and few are in the west, western cotton growers have few options if their cottonseed has high aflatoxin levels.

Several methods for controlling aflatoxin in cottonseed are currently available and several additional methods are under consideration. One of the most important and efficacious techniques is to apply strain AF36, an atoxigenic strain of *A. flavus*, to cotton fields. AF36 competitively excludes toxigenic strains, thus preventing aflatoxin production (Cotty et al., 2007). Ammoniation, a process by which aflatoxin-contaminated cottonseed is subjected to an ammonia solution in an enclosed environment, has proven effective in converting aflatoxin to less toxic chemicals (Park and Price, 2001).

Peanuts

While aflatoxin levels in U.S. peanuts have not increased over time, management costs have. Peanuts are undergoing increasingly rigorous testing and segregation programs. These programs have also yielded economic benefits to the U.S. peanut industry overall. Although about 25% of U.S. peanuts are exported, with a significant fraction to the EU, with its relatively strict aflatoxin standards, export rejection costs for aflatoxin are insignificant compared with other costs. This is largely because of U.S. peanuts' Origin Certification Program (OCP), a program in agreement with the EU that allows EU peanut importers to test significantly fewer loads, because approved methods of aflatoxin testing are conducted in the United States. The OCP reduces lots rejected at the port of entry, reduces the disruption in supply, and reduces economic losses, while maintaining EU standards for consumer safety (Adams and Whitaker, 2004).

The peanut industry presents an interesting case study in how stakeholders' cost burdens from aflatoxin affect economic analysis. Unlike corn and cottonseed, peanut shellers, and not the growers, bear most of the costs associated with aflatoxin contamination: up to US$30 million annually (Lamb and Sternitzke, 2001). These costs include testing peanuts for aflatoxin concentration, remilling (resorting lots to remove highly contaminated nuts), blanching (removing the peanut skin to make sorting more effective), insurance for highly contaminated lots, and labor and management costs.

Currently, shellers and manufacturers, not growers, incur the costs associated with aflatoxin contamination of peanuts. This has been a traditional situation; shellers develop relationships with growers, and oftentimes prices are negotiated before processing.

While there are methods available for aflatoxin management, because peanut growers do not incur any of the associated costs, there is little incentive to implement control methods. In microeconomic theory, the Kaldor-Hicks criterion (Posner, 2007) addresses this issue, providing incentives to a stakeholder group (peanut growers in this case) to adopt an action that will garner economic benefits for everyone. This is described in greater detail later in this article.

Tree Nuts

Of all the commercial U.S. tree nuts, aflatoxin mainly affects almonds and pistachios. These tree nuts have several important similarities: (1) they are produced almost exclusively in California; (2) the bulk of aflatoxin-related loss is borne by handlers, who buy even low-quality nuts from growers in order to maintain relationships on a long-term basis; (3) aflatoxin contamination is highly correlated with insect damage; (4) sorting to remove "inedibles" (including, indirectly, nuts with aflatoxin) is fairly easy and mechanized; and (5) most importantly from an economic standpoint, export markets play a key role in determining the market loss due to aflatoxin—particularly exports to the EU, which imports a large percentage of U.S. tree nuts and has one of the strictest aflatoxin standards for tree nuts (4 ng/g). Forty-five percent of U.S. pistachios are exported, and of this amount, 67% are exported to the EU (U.S. Department of Agriculture [USDA], 2005b). Seventy percent of U.S. almonds are exported: 62% to the EU (USDA, 2005a). It is on this last point—exports to the EU—that significant differences exist in aflatoxin's economic impacts on pistachios compared with those of almonds (or compared with those of cotton, corn, and peanuts).

EU food and feed imports are informed in part through the EU's Rapid Alert System for Food and Feed (RASFF). The RASFF is a tool used to exchange information on potential risks entering the food and feed system at any point in the EU, so that all EU member states may be alerted to take the appropriate measures to assure food and feed safety (Wu, 2008). In 2005, mycotoxins, especially aflatoxin, became a contaminant of specific interest that received an increased occurrence of RASFF notifications. In that year, the RASFF received a total of 993 notifications on mycotoxins, 947 of which concerned aflatoxin (European Committee [EC], 2006). In the last several years, the U.S. almond industry has experienced a large number of RASFF rapid alerts and information notifications (28 notifications in 2005 [EC, 2006], 36 notifications in 2006 [EC, 2007a], and over 60 notifications in 2007 [EC, 2007b]), which amount to \$10,000 to \$15,000 in rejection costs each (Wu, 2008). The rejection costs include testing and sampling, transportation, demurrage (storage, time, and labor costs), and financial adjustments and reprocessing of noncompliant shipments (Merle Jacobs, American Council for Food Safety and Quality, personal communication).

In January 2007, the EU proposed that "special measures" be applied to U.S. almond imports, as the EU Food and Veterinary Office (FVO) visit in the previous month (December 2006) led officials to the conclusion that U.S. almond aflatoxin control was inadequate. The EU measures require 100% surveillance: every almond consignment from the United States would be tested for aflatoxin. In September 2007, however, the Almond Board of California's Voluntary Aflatoxin Sampling Plan (VASP) went into effect. VASP provides an alternative aflatoxin sampling plan for the U.S. almond industry with an equivalent sensitivity to that being used in the EU. EU Regulation (EC/401/2006) was used as the guideline for lot size and sample frequency (Almond Board of California, 2007). The goal of VASP is to reduce the number of almond lots rejected by the EU. In part, the VASP guidelines were developed in response to EU concerns about U.S. almond quality. Now with VASP, U.S. almonds that have been tested under the VASP protocol prior to shipment and accompanied by a VASP certificate are subject to only 5% surveillance (Almond Board of California, 2007; Wu, 2008).

The U.S. pistachio industry, which has experienced far fewer EU notifications for aflatoxin (~10/year), hopes to establish an OCP with the EU, similar to the peanut industry (Robert Klein, California Pistachio Commission, personal communication). With an OCP, the aflatoxin testing would almost entirely occur on the exporter's end, with only occasional tests on the importer's (EU) end. Symbolically, it represents the EU's trust in the quality of U.S. pistachios.

TABLE 1 Preharvest and Postharvest Aflatoxin Control Methods in Food Crops (Wu and Liu, 2007)

Preharvest	Postharvest
Enhancing host resistance Conventional plant breeding (limited success) Genetic engineering methods (transgenic or genetically modified crops)	Physical methods Improved storage and transportation (e.g., reduced humidity and temperature) Sorting to remove damaged kernels Monitoring Decontamination in food processing (e.g., extrusion, fractionation)
Altering growing environment Good agronomic practices (e.g., hybrid choice, tillage, planting date, irrigation, crop rotation) Biocontrol Chemical control (e.g., antioxidants, insecticides, fungicides)	Chemical methods Detoxification (e.g., ammoniation, ozonation) Food additives to bind or adsorb aflatoxin (e.g., clay, chlorophyllin)

Economic Incentives to Adopt Aflatoxin Control Methods

Within particular commodities, there may be a mismatch in economic incentives to control aflatoxin. The most widely used agricultural methods to control aflatoxin in the U.S. occur during preharvest conditions (see Table 1, left columns). It is the growers of each commodity above that have the potential to control whether preharvest aflatoxin reduction methods are applied. Yet, if it is not the growers who also bear the burden of aflatoxin-related costs, then there is likely little motivation to control aflatoxin.

For example, in the corn and cottonseed industries, growers do bear the primary economic burden of aflatoxin contamination. Their lots are rejected if aflatoxin levels exceed thresholds for food and feed uses. However, in the peanut, almond, and pistachio industries, it is the shellers and handlers who bear the burden of the aflatoxin cost as mentioned above, because of the traditional relationship between shellers/handlers and growers and the practice of negotiating prices before processing. Therefore, peanut and tree nut growers may have no economic incentive to apply preharvest aflatoxin control, which itself has a cost. Postharvest aflatoxin control methods exist, but they provide limited options, and many have not yet been approved at the federal regulatory level.

The Kaldor-Hicks efficiency criterion can be applied to justify the adoption of certain aflatoxin control methods. This is a kind of economic efficiency in which one sector, for example, shellers and handlers, can compensate another (growers) to achieve *Pareto optimality*: a state in which at least one sector is left better off, and no one is worse off (Posner, 2007). In practice, Pareto optimality is almost impossible to achieve, as virtually any action might make someone less well off even if the net effect is beneficial. The Kaldor-Hicks efficiency criterion, a modern-day justification for benefit-cost analysis, circumvents this problem by stating that optimality is achieved if the winners in a transaction could, in theory, compensate the losers, making everyone better off. Applying this criterion to aflatoxin control in the peanut and tree nut industries, the shellers and handlers could pay growers to apply preharvest aflatoxin control methods. This would realign economic incentives such that those with the motivation to control aflatoxin would have the ability to do so through compensating others.

However, for the Kaldor-Hicks efficiency criterion to work in these cases, the aflatoxin control methods must be cost-effective; that is, the economic benefits of reduced aflatoxin must outweigh the costs of applying the method. Moreover, for the aflatoxin control method in question, the benefits must outweigh the costs for every party involved.

Aflatoxin Control Methods

Preventing aflatoxin accumulation in crops can be achieved via the use of any of several tactics alone or in combination (reviewed in Munkvold, 2003; Cleveland et al., 2003; Strosnider et al., 2006). Plant fungal diseases can be managed through host genetic resistance and/or cultural, biological, and chemical control methods.

Postharvest handling of crops offers additional challenges, but also opportunities to minimize the ultimate aflatoxin levels. An integrated, multifaceted strategy incorporating pre- and postharvest tactics would likely be the most successful approach (Wu and Munkvold, 2008).

Aflatoxin control methods are summarized in Table 1. The general strategy for preharvest aflatoxin control methods is to alter the conditions under which the crop is grown so that infection is avoided. Cultural controls include proper hybrid selection, tillage practices, fertilization regimes, crop rotation, proper plant density, planting date, and irrigation. Individual or combined effects of various cultural practices have been investigated for all three major mycotoxin-producing fungi in corn (Munkvold, 2003). In general, these methods are partially successful, especially when multiple tactics are applied together.

The case studies described in this paper will focus on two methods in particular: genetic engineering methods (specifically, Bt corn) and biocontrol.

Insect damage is one factor that predisposes plants to aflatoxin contamination, because insect herbivory creates wounds that encourage fungal colonization, and insects themselves serve as vectors of fungal spores (Wicklow, 1994; Sinha, 1998). Transgenic corn contains a gene from the soil bacterium *Bacillus thuringiensis* (Bt), which encodes for formation of a crystal (Cry) protein that is toxic to common lepidopteran and coleopteran corn pests. With the advent of Bt corn, growers experienced improved yields; and because Bt corn reduces insect related feeding damage, there was an indirect benefit in the reduction of the mycotoxins aflatoxin, fumonisin, deoxynivalenol, and zearalenone, as summarized in Munkvold (2003), Wu and colleagues (2004), and Wu (2007). Bt hybrids currently in late stages of development have shown significantly lower aflatoxin levels compared with non-Bt isolines (Headrick, 2006; Odvody and Chilcutt, 2007). Transgenic Bt peanut varieties are also being developed to resist aflatoxin. These transgenic crops could prove useful tools in reducing the disease burden associated with aflatoxin consumption in less developed countries.

Biocontrol methods for aflatoxin reduction in corn, peanuts, and pistachios have also been demonstrated under field conditions. Cotty and Bhatnagar (1994) found multiple strains of atoxigenic *A. flavus* that could inhibit aflatoxin production in vitro, but one in particular, AF36, which also inhibits aflatoxin production in the field, through competition with toxigenic strains. Dorner and colleagues (1999) found successful aflatoxin reduction in corn through use of atoxigenic *A. flavus* strains in preharvest field conditions. The atoxigenic strain AF36 has been shown to have a defective polyketide synthase gene (Ehrlich and Cotty, 2004), which prevents aflatoxin biosynthesis. Inoculating corn with atoxigenic strains of *A. flavus* has been shown to reduce aflatoxin contamination (Abbas et al., 2006). Importantly, atoxigenic *A. flavus* strains have been found in sub-Saharan Africa, which shows promise for controlling aflatoxin in African corn and peanuts (Dr. Ranajit Bandhyopadhyay, International Institute of Tropical Agriculture, Ibadan, Nigeria, personal communication).

Cost-Effectiveness of Aflatoxin Control: Case Studies

Here we will present three case studies that demonstrate a cost-effective reduction in aflatoxin concentration: AF36 in cottonseed, Bt corn, and Afla-Guard in peanuts. AF36 and Afla-Guard both employ biocontrol methods, while Bt corn is a transgenic corn variety that produces a plant-incorporated protectant.

AF36 in Cottonseed

As described above, application of AF36 is a biocontrol method that is currently adopted by cotton growers in several states and may soon receive limited approval for other crops such as corn and tree nuts. In this product, wheat seeds are coated with conidia of the AF36 atoxigenic strain of *A. flavus*, and these seeds are applied to cotton fields at a strategic time so that the atoxigenic strains competitively exclude toxigenic strains. Significant reductions in aflatoxin contamination in cottonseed have been achieved where AF36 has been approved for application to cotton (Arizona, Texas, and California) (Cotty et al., 2007).

Cottonseed growers in states that have historically faced unacceptable levels of aflatoxin contamination have become largely convinced of the efficacy of AF36 (Dr. Peter Cotty, University of Arizona, personal communication). The pressing economic question to cotton growers is whether they would wish to apply it every year, given that aflatoxin contamination can vary considerably from year to year. Therefore, we ask: would growers have incentives to apply it on a yearly basis? There are three economic factors to consider: the expected cost of aflatoxin contamination to cottonseed growers absent any interventions, the cost of purchasing and applying AF36, and the expected net benefit of applying AF36 in terms of aflatoxin reduction.

To calculate the cost of aflatoxin contamination per acre absent AF36 or other interventions, three variables are needed:

Y = cottonseed yield on a per-unit-area basis

P = price differential for cottonseed used for dairy feed (lowest aflatoxin contamination) versus other cottonseed uses

r = percentage of cottonseed that has aflatoxin levels above 20 ng/g—the limit for aflatoxin in dairy feed

Then, the cost per acre (C) associated with aflatoxin contamination to cottonseed growers can be expressed as:

$$C = Y^{*} P^{*} R \tag{1}$$

We apply Eq. 1 to calculate the cost of aflatoxin contamination in Arizona cottonseed using the following assumptions: the average cottonseed yield is one ton per acre, the price differential for dairy feed compared with other uses is \$30 to \$80 per ton in 2008 U.S. dollars, and the proportion of Arizona cottonseed that exceeded 20 ng/g aflatoxin contamination from 1990 to 1997 was 55.1% (Dr. Larry Antilla, Arizona Cotton Research & Protection Council, personal communication). Therefore, the total expected loss due to aflatoxin contamination, assuming no control methods, is \$16 to \$48 per acre.

This number is compared with the benefits and costs of applying a control method such as AF36. The cost of applying AF36 depends on two variables: the material cost of the AF36 itself, and the cost of application. The current material cost of AF36 is about \$5 per acre. The cost of application can vary from \$1/acre if applied using tractors to as high as \$10/acre if applied aerially (Dr. Peter Cotty, University of Arizona, personal communication). Thus, the total cost of applying AF36 to a field ranges from about \$6 to \$15/acre.

The net benefit of applying AF36—that is, the difference between the economic values of cottonseed with or without AF36 application, due to different aflatoxin levels—can be calculated by looking at past data on AF36 effectiveness in reducing aflatoxin to acceptable levels. This net benefit, B, depends on several factors:

E = the percent efficacy in reducing aflatoxin to levels that allow growers a premium
C = cost associated with aflatoxin (shown in Eq. 1 above)
A = total cost of applying AF36 (calculated above)

Thus, the net benefit per acre of AF36 application can be expressed as:

$$B = (E * C) - A \tag{2}$$

On average, AF36 can effectively reduce aflatoxin levels to below 20 ng/g 90% of the time when aflatoxin levels would not otherwise have met the 20 ng/g standard (Cotty et al., 2007). Therefore, the estimated net benefit of AF36 in reducing aflatoxin ranges from –\$0.62 to \$34 per acre. The negative value in the low end of this range accounts for the fact that in some years, aflatoxin would not be expected to cause a large problem; so the cost of application (especially if growers use aerial application methods) would slightly exceed the benefits. In other words, in almost all cases, the expected benefit of applying AF36 exceeds the cost.

It is important to note that expected benefits of applying AF36, and expected cost due to aflatoxin in cottonseed, are likely to change with time based on AF36 application. If AF36 is applied regularly in a particular region, the soil ecology may change such that the proportion of toxigenic versus atoxigenic strains will decrease (Cotty et al., 2007). Another point to consider is the cost of AF36 application compared with the total value of cottonseed production per acre: roughly \$120 to \$200 per acre in Arizona (USDA National Agricultural Statistical Service online query, http://www.nass.usda.gov). Hence, even in years in which aflatoxin would be naturally low, the cost of AF36 application represents 3% to 12% of the total value of cottonseed production. To improve cost-effectiveness of AF36, cotton growers should aim for the lowest application cost (~$1 per acre). If the cottonseed industry was interested in promoting AF36 and other cost-effective techniques to reduce aflatoxin, one way they could communicate with growers about AF36 is as an "insurance policy" to protect against aflatoxin-related costs.

Bt Corn

As described above, commercially available Bt corn events (an "event" is a successful transformation of a transgenic plant) have shown significantly lower levels of the mycotoxins fumonisin, deoxynivalenol, and zearalenone in several field and feed studies worldwide, compared with non-Bt isolines. A new event in late development has shown significant aflatoxin control as well. We ask: how effective must it be to make it economically worthwhile for corn growers? The type of question asked in this cost-effectiveness case study is different from the one above in AF36, because the new Bt corn event is not yet commercially available. Hence, the market price is not yet known. Moreover, because it is not yet commercially available, little information is available about aflatoxin reduction to acceptable levels in the marketplace. Nonetheless, it is useful to assess cost-effectiveness under different conditions of price and aflatoxin reduction effectiveness.

The new Bt corn event, in a late stage of development as of April 2008, produces two crystal proteins (Cry1A.105 and Cry2Ab2) that provide significantly improved protection against corn ear worm (CEW) and fall armyworm (FAW) compared with commercially available events (Odvody and Chilcutt, 2007). Controlling these pests is expected to reduce aflatoxin contamination in the field because CEW and FAW damage is associated with *A. flavus* colonization and subsequent aflatoxin contamination in corn. In addition to these two proteins, the new event produces other crystal proteins that are produced by currently commercially available Bt corn varieties that control European corn borer (ECB) and Southwestern corn borer (SWCB).

In field trials conducted in 2005 and 2006, Odvody and Chilcutt (2007) tested the new Bt corn event with other Bt hybrids and conventional hybrids at two different locations under conditions (late planting dates and inoculum of a high aflatoxin-producing isolate of *A. flavus*) designed to be conducive to extremely high aflatoxin levels. In 2005, the new event showed significantly lower aflatoxin levels at one location, compared with the other hybrids, but no differences were observed among the corn lines tested at the second location. In 2006, the new event showed significantly lower aflatoxin levels (average 646 ng/g) compared with other Bt hybrids (898 ng/g) and conventional hybrids (1220 ng/g) in both locations. These aflatoxin levels are still very high compared with the FDA action levels; hence, more research is needed to determine the efficacy of the new Bt event in reducing aflatoxin in ordinary field conditions.

Bt corn seed costs more than conventional corn seed, and the more "stacked" traits or inserted genes an event has, the more expensive it is. Thus, not all growers will be expected to buy the new event as not all growers have a problem with the insect pests that predispose corn to aflatoxin. Aflatoxin is primarily a problem in corn grown in the southern and southeastern United States, although occasionally it presents a problem in corn grown in the Corn Belt as well. So the new event is likely to be used far more in southern corn fields than in other parts of the United States.

How effective must this Bt corn event be at reducing aflatoxin to make it "worth it" for growers? This depends on what aflatoxin would cost growers in the marketplace. Food-grade corn, which must have aflatoxin levels below 20 ng/g, receives the highest market price. As described above, if aflatoxin levels are too high in food so that it must be sold for feed instead, growers receive about $1 per bushel less. In many parts of the south and southeast, aflatoxin levels in corn can be so high (>300 ng/g) that it cannot be sold even for animal feed. In that case, growers may lose $3 per bushel, though the range is large depending on location and season.

If average yield is assumed to be 130 bushels of corn per acre, and the new Bt seed costs as high as $20 per acre more than conventional seed, then the seed premium per bushel for Bt corn is about $0.15 per bushel. Compared with potential losses of $1 to $3 per bushel for aflatoxin-contaminated corn, the added cost of the new event is minimal. In other words, the event is cost-effective if it can reduce aflatoxin-related problems by 5% or more, aside from its other grain quality improvements. Odvody and Chilcutt's (2007) field trial results indicate that the potential aflatoxin reduction could be much higher than just 5%.

In many parts of the Corn Belt, growers see no need to reduce aflatoxin, as their aflatoxin levels are already low enough to meet feed-grade standards. However, in other parts of the United States where aflatoxin is frequently a contaminant in corn, the new event would be cost-effective at this price listed above. In today's ethanol boom, the problem of controlling aflatoxin in corn is more important than ever, as ethanol co-products are used in animal feed and have even higher mycotoxin levels than the original grain. Hence, any tools that can help to reduce aflatoxin and other mycotoxins in corn would have a potential added benefit in terms of livestock health (Wu and Munkvold 2008).

Afla-Guard in Peanuts

Afla-Guard, another commercially available form of aflatoxin biocontrol, is applied primarily to peanut fields in the United States. Pearl barley grains are coated with conidia of an atoxigenic strain of *A. flavus*, and these grains are applied to peanut fields to provide competitive exclusion of toxigenic strains.

Aflatoxin problems in U.S. peanuts are erratic. Most peanuts are grown in the southeastern United States; yet even within this region, aflatoxin levels in peanuts can vary significantly from state to state, as well as year to year. These variations are captured by Lamb and Sternitzke (2001), who estimated costs associated with aflatoxin in peanuts on a state-by-state basis from 1993 to 1996. For example, costs of aflatoxin in Florida peanuts in 1994 were estimated at $15.06 per acre (all values have been adjusted to 2008 dollars), while costs of aflatoxin in Alabama peanuts in 1995 were as high as $71.45 per acre. Thus, it is very difficult to predict how problematic aflatoxin will be in any given year, which may lead to lower motivation to apply aflatoxin control methods. If a cost-effective method could be found that would have almost always lower costs than benefits, this would be useful to the peanut industry on a yearly basis.

We apply Eqs. 1 and 2 from above to evaluate Afla-Guard's cost-effectiveness. The cost of aflatoxin in peanuts, described in the above paragraph, can vary from about $15 to $72 per acre.

By comparison, the material cost of Afla-Guard ranges from $15 to $20 per acre (Dr. Joseph Dorner, personal communication), while the application cost ranges from $1 (ground application) to $10 (aerial application) per acre. Thus, the total cost of Afla-Guard ranges from $16 to $30 per acre. Assuming that Afla-Guard can reduce aflatoxin costs by 90%, the economic benefit that it provides in reducing aflatoxin is $13.50 to $65 per acre. Thus, the net benefit of Afla-Guard application, or the benefits minus the costs, ranges from –$16.50 to $49 per acre. The negative value in the low end of this range indicates that the combination of Afla-Guard's cost and the possibility of applying it in a low-aflatoxin region or year occasionally renders the cost higher than the benefit.

Further complicating the issue is that growers do not bear the largest burden of aflatoxin cost. Shellers bear most, but not all of the cost of aflatoxin in peanuts, as they must maintain relationships with growers and are accustomed to accepting even more highly contaminated nuts, which they must then deal with as appropriate. Specifically, Lamb and Sternitzke (2001) estimate that of the costs associated with aflatoxin, growers bear on average about 11%, buyers about 2%, and shellers about 87%. Therefore, growers themselves have little motivation to apply aflatoxin control methods. Even if shellers paid for the full cost of aflatoxin control, they would only receive 87% of the benefit in terms of reduced aflatoxin contamination. For example, of the economic benefit that Afla-Guard provides, shellers would experience 87%, or $11.75 to $56.55 per acre. Thus, their net benefit would be –$18.25 to $40.55 per acre—lower than the net benefit of Afla-Guard as a whole.

This case study presents an interesting application of the Kaldor-Hicks criterion described earlier. Depending on the year and the region, shellers may benefit only at the margin if they pay the entire cost of applying Afla-Guard. Adoption of this aflatoxin control method would likely increase if material costs decrease, and if shellers (or others paying for the technology) aimed for lowest costs of application (ground application). The large variability by region also indicates that Afla-Guard, as well as other aflatoxin control methods, would be much more cost-effective in certain states than others. In regions where aflatoxin is more commonly a problem, Afla-Guard could be applied more regularly as a method of insuring their crops against excessive aflatoxin damage, which on average would prove economically beneficial

Discussion

Economic incentives to control aflatoxin can be complicated. Both preharvest and postharvest aflatoxin control methods exist, although the bulk of effective methods are preharvest. For certain commodities, growers may not have the motivation to apply these preharvest methods, because they do not bear the largest burden of aflatoxin-related cost. But applying the Kaldor-Hicks criterion, markets can be realigned so that the sectors that do bear the largest burden could pay growers to apply aflatoxin controls, or could pay for and apply those controls themselves. Thus, it becomes important to evaluate the cost-effectiveness of different aflatoxin control methods. If the benefit exceeds the cost, there is almost always a cost-effective way that the method can be applied, no matter which sector bears the burden of aflatoxin cost.

Our three case studies demonstrate how cost-effectiveness of aflatoxin control methods can be evaluated, even in absence of perfect information. These cases focused on control methods in cottonseed, corn, and peanuts; tree nuts are another important commodity for which cost-effective aflatoxin control methods should be researched in the future. Each case we discuss is different in terms of what is known about benefits and costs, and which sector would benefit most from aflatoxin control. Our analysis suggests ways in which to think about, estimate, and communicate cost-effectiveness: as an insurance policy, where to cut costs if possible, how to compare expected benefits and costs, and how benefits and costs apply to specific sectors.

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